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# Structural inverse analysis by hybrid simplex artificial bee colony algorithms

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ABSTRACT

A hybrid simplex artificial bee colony algorithm (HSABCA) which combines Nelder–Mead simplex method with artificial bee colony algorithm (ABCA) is proposed for inverse analysis problems. The proposed algorithm is applied to parameter identification of concrete dam-foundation systems. To verify the performance of HSABCA, it is compared with the basic ABCA and a real coded genetic algorithm (RCGA) on two examples: a gravity dam and an arc dam. Results show that the proposed algorithm is an efficient tool for inverse analysis and it performs much better than ABCA and RCGA on such problems.



## 1. Introduction

The quantitative assessment of constitutive parameters by inverse analysis exhibits at present growing scientific interest and practical usefulness, as material models become more realistic and complex, and computational tools more and more powerful [1]. In general, forward modeling allows us to answer questions such as "what response should be expected from this distribution of material properties under these initial conditions?" Reverse problems require an answer to a question that goes in the opposite direction. Reverse analysis has been widely used in diverse fields, such as geological process modeling [2], structural damage or crack detection [3–5], drainage system design [6], excavation support system simulation [7], parameter identification of earth-rockfill dams [8] and concrete dams [9–11].

The Young modulus is a necessary parameter in structural analysis for the determination of the stress distributions and displacements, especially when the design of the structure is based on elasticity considerations. In a dam-foundation system, the modulus of elasticity of dam concrete is hard to be determined directly from tests due to the necessity for large specimens and testing machines [12]; the modulus of the rock is also hard to be determined because of the complicated geological situations. Inverse analysis is a powerful tool to determine the mechanical parameters of dam-foundation systems. Through inverse analysis, exact parameters of dam-foundation systems can be determined, and a precise evaluation on the safety condition of dams can be made. Several strategies have been developed for the diagnostic inverse analysis of concrete dams. A damage diagnosis approach for concrete dams by radar monitoring is proposed by Ardito et al. [10,13]. An overall inverse analysis method for concrete dams based on neural networks is proposed by Fedele et al. [9,14]. An inverse analysis method for the identification of stress states and elastic properties in concrete dams by flat-jack test is developed by Fedele and Maier [11].

In recent years, reverse analysis is mainly based on two methodologies: neural networks [8,9,15] and optimization algorithms. In this paper, we focus on optimization-based inverse analysis. There are three types of optimization algorithms that have been used in reverse analysis. The first type is gradient-based direct search algorithms, such as Levenberg–Marquardt method [16], conjugate gradient method [17] and trust region method [10,13]. The second type is the relatively simple direct search methods making no use of gradient, such as the simplex search method [18,19]. The last type is intelligent global search algorithms, such as genetic algorithms [7,20,21], differential evolution [22], particle swarm optimization [23] and ant colony optimization [24]. The first and the second type algorithms both have an advantage of estimating the solutions in relatively short computational time, but the results are affected by the initial values and premature convergence is likely to happen. As an alternative to the direct search algorithms, intelligent global search algorithms are being widely adopted in reverse analysis, but they have a disadvantage of being time-consuming.

In this paper, parameter identification method for concrete dam-foundation systems based on statistical analysis of recorded dam displacements with a hybrid optimization algorithm is proposed. A novel artificial bee colony algorithm (ABCA) [25] inspired by honey bee foraging is adopted for inverse analysis problems. It has been demonstrated that ABCA outperforms genetic algorithm,

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particle swarm optimization in multivariable function optimization [26,27]. In order to combine the advantages of direct search methods with intelligent global optimization algorithms, a hybrid simplex artificial bee colony algorithm (HSABCA) which combines ABCA with Nelder–Mead simplex search method (NMSS) [28–30] is proposed for inverse problems. The proposed algorithm is applied to inverse analysis of a concrete gravity dam and a concrete arc dam. In the examples, pseudo-experimental data are adopted to inverse analysis. The pseudo-experimental displacements are obtained through forward finite element analysis by setting water level and material parameters to certain values. That means no experimentally recorded dam displacements are used in the study. The result obtained by HSABCA is also compared with NMSS, ABCA and a real coded genetic algorithm (RCGA).

This paper is organized as follows. Section 2 presents the theory of inverse analysis for concrete dams. Section 3 introduces ABCA. Section 4 introduces NMSS, and then HSABCA is developed. Section 5 shows the performance of NMSS, RCGA, ABCA and HSABCA on inverse analysis problems of concrete dams. Finally, conclusions are given in Section 6.

## 2. Inverse analysis of concrete dams

### 2.1. Statistical analysis of recorded concrete dam displacement

Structural health monitoring of large concrete dams is based on acquisition of displacement measurements. These displacements are interpreted to identify significant deviations from what could be considered as the normal response from statistical or deterministic models of the dam behavior.

In the HST (hydrostatic, seasonal, time) statistical model, recorded dam displacements are treated as the aggregation of presumably reversible hydrostatic, $u(h)$, seasonal (associated predominantly with thermal) effects $u(s)$, and irreversible effects, $u(t)$, due to residual deformations in time associated with creep, alkali-aggregate reaction and other nonlinear effects that may jeopardize the structural integrity. The HST model could be written as [31]

$$u(h,s,t) = \alpha_0 + u(h) + u(s) + u(t) \tag{1}$$

$$\begin{aligned} u(h,s,t) = \alpha_0 &+ [\alpha_1 h(t) + \alpha_2 h^2(t) + \alpha_3 h^3(t) + \alpha_4 h^4(t)] \\ &+ (\alpha_5 \cos s + \alpha_6 \sin s + \alpha_7 \sin^2 s + \alpha_8 \sin s \cos s) \\ &+ (\alpha_9 t + \alpha_{10} e^{-t}) \end{aligned} \tag{2}$$

where $h$ is reservoir level; $s$ is season varying between 0 and $2\pi$ from January 1 to December 31 according to $s = 2\pi j/365$ with $j$ being the number of days since January 1; $h(t)$ is the reservoir level at time $t$. Although different expressions have been proposed for $u(t)$ in the literature, Eq. (2) is found adequate from the practical point of view.

Statistical models are developed from a linear regression analysis to compute coefficients $\alpha_0$ to $\alpha_{10}$ from previously recorded displacements allowing to separate reversible $u(h)$, $u(s)$ and irreversible $u(t)$, displacement components. The separated $u(h)$ under certain reservoir level $h$ is adopted to obtain an estimation of true physical parameters, such as the elastic Young modulus, an overall indicator of structural integrity, based on finite element models of the structure and structural identification technique.

### 2.2. Mathematical model for inverse analysis of concrete dam

Finite element analysis method is adopted to solve the direct problem of a dam-foundation system. The analytical static model in the finite element formulation is

$$\boldsymbol{K}\boldsymbol{u} = \mathbf{P} \tag{3}$$

where $\boldsymbol{K}$ is the structural stiffness matrix, $\boldsymbol{u}$ is the displacement vector, and $\boldsymbol{P}$ is the load vector.

The stiffness matrix of the $i$th element can be expressed as

$$\boldsymbol{k} = \int\int\int \boldsymbol{B}^T \boldsymbol{D}\boldsymbol{B} dx\,dy\,dz \tag{4}$$

$$\boldsymbol{D} = f(E, \boldsymbol{\mu}) \tag{5}$$

where $\boldsymbol{B}$ is the strain–displacement matrix; $\boldsymbol{D}$ is the stress–stain matrix; $E$ is the Young modulus and $\mu$ is the Poisson ratio.

Isotropy is assumed, and the Poisson ratio, which plays a minor role in the overall structural response, is regarded as known [13]. The Young modulus of the concrete dam and foundation are regarded as zone-wise homogeneous distribution and unknown. They can be estimated by minimizing the objective function, which is expressed by the sum of square errors between numerical displacements and measured displacements at certain points of the concrete dam. The mathematical model for inverse analysis of concrete dams can be expressed as

$$\min \quad f(\boldsymbol{x}) = w_i \sum_{i=1}^{np} ((u_{i,e} - u_{i,n})/u_{i,e}) \tag{6}$$

$$\text{s.t.} \quad \boldsymbol{K}\boldsymbol{u} = \boldsymbol{P} \tag{7}$$

$$a_i \leqslant x_i \leqslant b_i \quad (i = 1, 2, \ldots, k) \tag{8}$$

where $\boldsymbol{x}$ is the vector of material parameters; $np$ is the number of points to be measured; $u_{i,e}$ and $u_{i,n}$ are the experimental and numerical displacements of the $i$th point; $w_i$ is the weight of the $i$th point; $a_i$ and $b_i$ are the lower and upper boundary values of the $i$th parameter; $k$ is the number of parameters to be identified.

In practice, $u_{i,e}$ is obtained from Eq. (2). It is the displacement $u(h)$ at point $i$ which is related to the hydrostatic pressure. In the following examples, pseudo-experimental data are adopted to inverse analysis [9,10]. The pseudo-experimental $u_{i,e}$ is obtained through forward finite element analysis by setting water level $h$ and material parameters to certain values.

## 3. Artificial bee colony algorithm

### 3.1. Behavior of real bees

Honey bees are creatures of unexpected complexity-models of domesticity who are able to produce food, learn, navigate, and communicate through intricate dances. Indeed, their colonies represent the ultimate socialist state, with complete selflessness and redistribution of "income" [32]. Virtually all bees in this colonial organism are female: a single queen and the tens of thousands of workers in the hive are females. During a portion of the year, a few hundreds (in large hives perhaps as many as a few thousands) males – the drones – are reared. The worker bees build the honeycomb, rear the young, clean the colony, feed the queen and drones, guard the hive, and collect food. At perhaps three weeks of age, a worker bee begins foraging, making trip after trip to collect food.

The minimal model of forage selection that lead to the emergence of collective intelligence of honey bee swarms consists of three essential components: food sources, employed forages and unemployed forages [25]. The value of a food source depends on many factors. For the simplicity, the "profitability" of a food source can be represented with a single quantity. Employed forages are associated with a particular food source, which are currently exploited. They carry with them the information about this particular source and share the information with a certain probability. Unemployed foragers are looking for a food source to exploit. There are two types of unemployed foragers: scouts searching the envi-